Fluid electrodes for submersible robotics based on dielectric elastomer actuators

Caleb Christianson[a], Nathaniel Goldberg[b], Shengqiang Cai[b], and Michael T. Tolley[b]

[a]Department of NanoEngineering, University of California San Diego, 9500 Gilman Dr., La Jolla, California 92093

[b]Department of Mechanical and Aerospace Engineering, University of California San Diego, 9500 Gilman Dr., La Jolla, California 92093

ABSTRACT

Recently, dielectric elastomer actuators (DEAs) have gathered interest for soft robotics due to their low cost, light weight, large strain, low power consumption, and high energy density. However, developing reliable, compliant electrodes for DEAs remains an ongoing challenge due to issues with fabrication, uniformity of the conductive layer, and mechanical stiffening of the actuators caused by conductive materials with large Young's moduli. In this work, we present a method for preparing, patterning, and utilizing conductive fluid electrodes. Further, when we submerse the DEAs in a bath containing a conductive fluid connected to ground, the bath serves as a second electrode, obviating the need for depositing a conductive layer to serve as either of the electrodes required of most DEAs. When we apply a positive electrical potential to the conductive fluid in the actuator with respect to ground, the electric field across the dielectric membrane causes charge carriers in the solution to apply an electrostatic force on the membrane, which compresses the membrane and causes the actuator to deform. We have used this process to develop a tethered submersible robot that can swim in a tank of saltwater at a maximum measured speed of 9.2 mm/s. Since saltwater serves as the electrode, we overcome buoyancy issues that may be a challenge for pneumatically actuated soft robots and traditional, rigid robotics. This research opens the door to low-power underwater robots for search and rescue and environmental monitoring applications.

Keywords: dielectric elastomer actuators, soft robotics, fluid electrodes, underwater robotics

1. INTRODUCTION

Dielectric elastomer actuators (DEAs) are a promising enabling technology for soft robotics, microfluidics, and optics, due to their large strains, high energy density, and high efficiency.[1–6] These properties extend to submersible applications, but implementation of DEAs in underwater applications has been limited, partially due to the challenge of identifying suitable, flexible electrode materials. The goal of this work is to leverage the advantages of DEAs to enable submersible soft robotics. We achieve this by incorporating fluid electrodes to obviate some of the inherent challenges with patterning robust stretchable electrodes while harnessing the grounding capabilities of a surrounding, conductive fluid.

Previous work has explored the use of novel materials in the fabrication of DEAs. Pelrine *et al.* first introduced the use of VHB, an acrylic adhesive foam from 3M, as a dielectric material,[7] which demonstrated the inherent adhesive properties of VHB while taking advantage of its exceptional dielectric and mechanical properties to achieve extreme voltage-induced deformations. Carpi *et al*. provided the first explicit use of conductive fluid electrodes for dielectric elastomers in a thickened electrolyte solution for planar actuators.[8] Keplinger *et al.* introduced ionic hydrogels for electrodes in high speed DE actuation,[9] providing an insightful foundation to the considerations of using ionic conductors for DEAs. More recently, Tavakol *et al.* demonstrated the effectiveness of ionic conductors for DEAs through an implementation of conductive fluid as the working electrodes in a DEA-driven microfluidics chip.[10] Godaba *et al.* established one of the first works on implementing DEAs on submersible robotics in a jellyfish-inspired robot.[11] Recently, Shintake *et al.* developed submersible, biomimetic fish- and jellyfish-inspired robots using DEAs.[12] As shown by *Godaba et al.* and *Shintake et al.*, DEAs can provide effectual actuation in submersible soft robots. However, these implementations rely upon carbon-based electrodes, which are challenging to pattern in complex geometries and are subject to mechanical abrasion.[13,14] Additionally, one major limitation of DEAs is the need for prestretching the elastomer to improve actuation, which necessitates mounting the actuator to a rigid frame or including a stiffer material to maintain the stretch. One recent example from Duduta *et al.* demonstrated that thin layers of an acrylic elastomer can be used to achieve effective strains without the need for prestretch.[15]

In this work, we present a method for preparing, patterning, and utilizing conductive fluid electrodes with a simple saline solution serving as the conducting fluid. Further, when we submerse the DEAs in a bath containing a conductive fluid connected to ground, the bath serves as the second electrode, obviating the need for the electrode pairs required of most DEAs. When we apply a potential to the conductive fluid in the actuator with respect to ground, the electric field across the dielectric membrane causes charge carriers in the solution to apply an electrostatic force on the membrane, which compresses the membrane and causes the dielectric layer to thin and expand laterally. Since the bimorph actuator consists of two active areas in an agonist-antagonist configuration, the unactivated layer constrains the extension of the activated layer and causes the actuator to bend. This allows us to achieve bidirectional bending through selective stimulation of the individual actuators. Since we use dielectric layers without prestretch, we eliminate the need for a rigid frame, resulting in a completely soft actuator. The remainder of this work will cover the design of the swimming actuator (Section 2), a simple analytical model that demonstrates the bending of our actuator (Section 3), the fabrication processes that we used (Section 4), and a discussion of our results in (Section 5).

2. DESIGN

Many recent efforts have worked to develop bioinspired, robotic fish, including using DEAs,[12,16] other smart actuators,[17] fluidic elastomer actuators,[18] and traditional electromechanical components.[19–21] This research builds upon the existing work of bioinspired, swimming robots to demonstrate the feasibility of DEAs with fluid electrodes for soft robotics. We implemented the fluid electrode DEA as a bimorph actuator to demonstrate the working principle, in which the actuator generates propulsion for a bioinspired, swimming robot. Since both the dielectric and electrode materials have densities that are comparable to the fluid that the actuator is submerged in, the actuator exhibits near neutral buoyancy, which we can tune by changing the volume of fluid in the actuator. We formed a unimorph actuator by encapsulating a fluid chamber within a dielectric layer and a strain limiting layer. To demonstrate bidirectional bending, we combined two unimorph actuators, back-to-back, to achieve a bimorph actuator in which the non-activated chamber constrains the lengthening of the activated chamber to induce a bending moment (see Figure 1). When we place the actuator in a bath of a grounded, conductive fluid and apply a voltage to one of the chambers with respect to the grounded bath, opposing charges accumulate at the interfaces of the dielectric layer, compressing it in thickness and causing it to expand in length. This expansion in length, when attached to a non-activated layer, induces a bending motion away from the activated side. By charging the antagonistic actuators in an alternating pattern, we can induce a bidirectional flapping motion, allowing the actuator to swim forward.

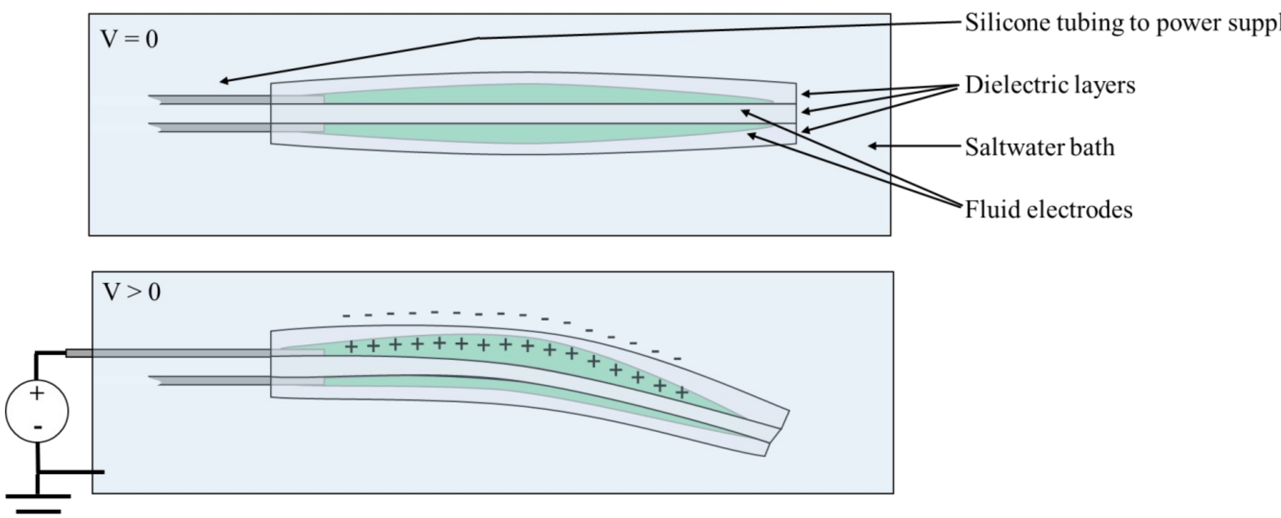

Figure 1. Design and working principle of bimorph DEA with fluid electrodes in a bath of a grounded, conductive fluid. Top: Three layers of acrylic tape and two fluid chambers make up a bimorph DE actuator. Bottom: A voltage applied between one of the chambers and the external bath causes opposite charges to attract, compressing the barrier dielectric layer in thickness and expanding it in area. The lower chamber constrains the expansion of the activated layer, causing the bimorph to curl away from the activated side.

3. ANALYTICAL MODEL

We compare our results to a simple analytical model that describes the curvature of a cantilever DEA as a function of voltage. Taking the longitudinal strain in the active layer of VHB as the characteristic strain, we obtain from Hooke's law:

$$\varepsilon_{xx} = \frac{\nu p}{E} \tag{1}$$

in which v is the Poisson ratio, E is the elastic modulus of VHB, and p is the equivalent mechanical pressure, as given by Pelrine's equation[1]:

$$p = \epsilon_0 \epsilon_r \left(\frac{V}{h}\right)^2 \tag{2}$$

where ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric layer, and V and h are the applied potential and thickness of the dielectric layer, respectively. By approximating the actuator as a constant-curvature, Euler-Bernoulli beam in pure bending, we find the curvature κ as proportional to the longitudinal strain, divided by the thickness of the beam:

$$\kappa \sim \frac{\nu p}{Eh} \tag{3}$$

which results in:

$$\kappa \sim \frac{\upsilon \epsilon_0 \epsilon_r V^2}{Eh^3} \tag{4}$$

We plot κ as a function of the initial electric field with a phenomenological scaling factor found by a least squares fitting of the experimental results in Figure 4. Since the curvature is invariant in the length of the actuator, we expect the analytical model to describe the relationship between applied voltage and measured curvature regardless of actuator length.

4. MATERIALS AND METHODS

We tested bimorph actuators consisting of three layers of double sided acrylic tape (VHB 4905, 3M) (see Figure 2). To designate the active area of the DEAs, we created masks using a digital laser machining system to cut stencils from masking tape. The non-adhesive side of the masking tape provided sufficient adhesion to the acrylic tape to enable masking while allowing easy removal after patterning. After affixing the mask to the acrylic tape, we applied the passivating layer to the exposed surface of the tape. To allow for insertion of the conductive fluid after sealing and to maintain a conductive connection between the inner actuator chamber and the power supply, we placed 0.5 mm diameter silicone tubing (STHT-C-020-0, STI Components) across the passivated/non-passivated interface and sealed any potential air gaps with a silicone epoxy (Sil-Poxy, Smooth-On, Inc.). We then applied the next layer of acrylic tape and repeated the process to produce bimorph actuators. Saltwater with a concentration of 35 mg/L, to approximate the conductivity of seawater, served as the conductive fluid inside the actuator and in the bath. We colored the fluid in the actuators with green food dye to serve as a visual aid. We then injected the internal fluid into the actuator through the attached silicone tubing using a syringe. Finally, we connected the high voltage power supply to the metallic needle tip of the syringe, as shown in Figure 3a, which maintained contact with the fluid electrodes throughout actuation. The conducting fluid infiltrated the passivated area of the DEA. When we applied a bias voltage between one of the actuators and the surrounding fluid, the dielectric VHB layer compressed in thickness and expanded in area, which caused an increase in length of the VHB. This lengthening induced a bending moment in the actuator, causing it to curve away from the side that was actuated, as shown in Figure 3b.

For testing the ability of the tethered robot to swim underwater, we used a microcontroller to provide a signal to a pair of DC/high voltage DC converters (EMCO Q101, XP Power). We connected the output high voltage signal to the lead of one side of the actuator, and repeated the same process for the other (antagonistic) DEA. Finally, to stiffen the leading edge of the actuator for this swimming experiment, we affixed 48 mm long pieces of nylon tie-wrap to the upper and lower leading edges of the actuator.

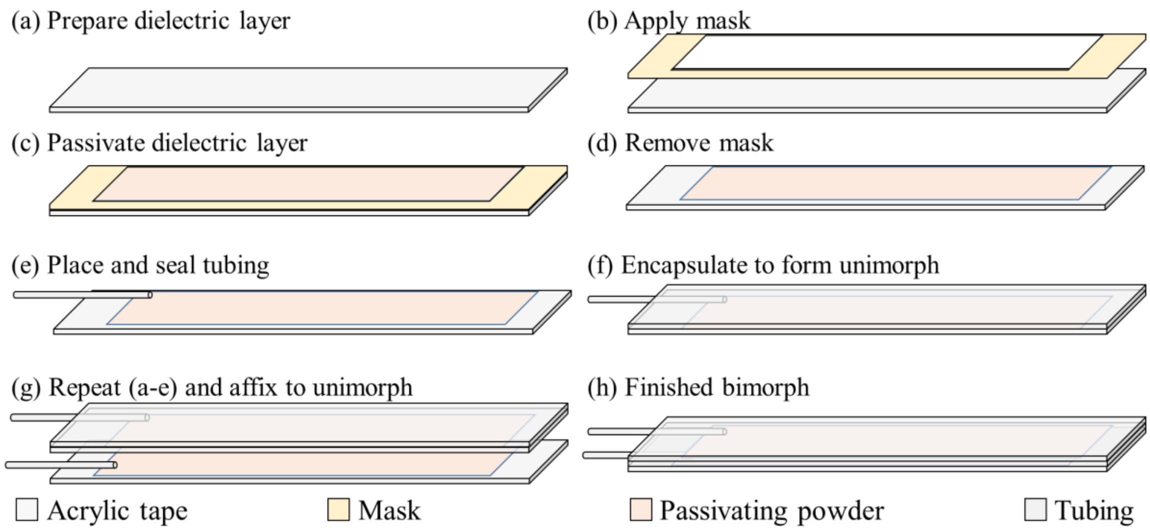

Figure 2. Bi-direction fluid electrode DEA fabrication. (a-h) The actuator is fabricated in eight steps: (a) Prepare the first acrylic adhesive layer; (b) add a mask patterned using a laser machining system; (c) apply a passivating layer to define the active area; (d) remove the mask; (e) place tubing for fluid and electrical connections and seal around tubing with silicone sealant, repeating steps (a-e) for bimorphs; (f) encapsulate with an additional acrylic adhesive layer, resulting in a unimorph fluid electrode DEA; (g) adhere unimorph to second partial structure created in step (e); and (h) resulting bimorph structure.

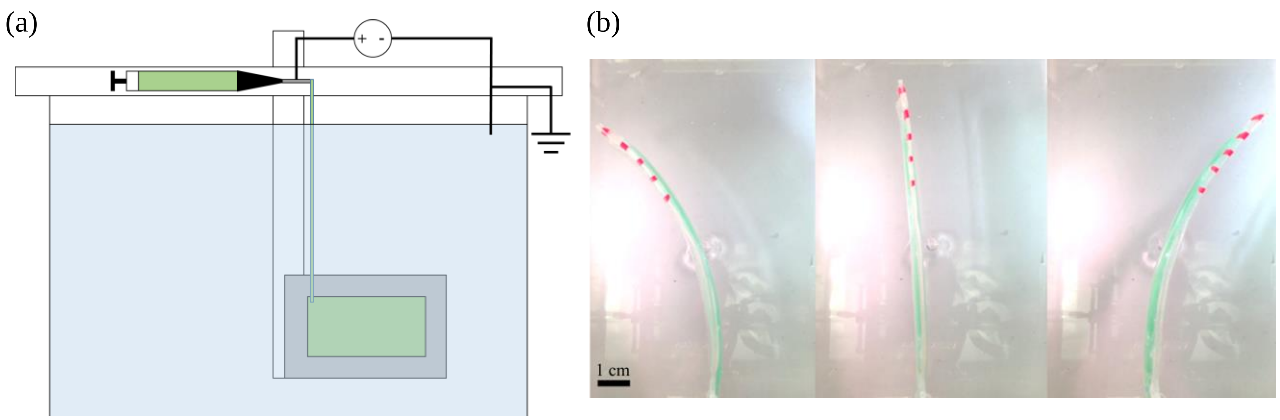

Figure 3. Experimental setup and representative images from curvature measurements. (a) We mounted the bimorph actuator to an acrylic arm and suspended it in a grounded saltwater bath. We injected the active area of the electrode with saltwater and connected it to the positive high voltage lead through the metallic tip of a syringe. (b) Still images from curvature measurements. An applied potential between the bottom actuator and the surrounding bath lengthens the actuator, causing the structure to bend to the left, as shown in the left-most photo. The center photo is representative of when the actuator is at rest. The right-most image is from when we apply a potential between the upper actuator and surrounding bath. Maximum actuation is achieved within 2-4 seconds.

5. RESULTS AND DISCUSSION

To investigate the dependence of the actuator geometry on the performance of DEAs with fluid electrodes, we fabricated three bimorph actuators, of various lengths (73 mm, 110 mm, and 143 mm), but with identical values of width (49 mm) and material thickness (0.5 mm). We characterized the curvature and motion of the actuators as a function of voltage and actuator length to determine their suitability for underwater actuation and propulsion by affixing the actuators to a rigid acrylic arm that was suspended in the testing bath, as shown in Figure 3. We used a high voltage power supply (ES20P-5W, Gamma High Voltage Research, Inc.) to provide power for the bimorph curvature measurements. We measured the curvature as a function of voltage for voltages ranging from 6 kV to 10 kV in 1 kV increments for all three of the actuators, as shown in Figure 4a. We selected the longest actuator (143 mm) for mobility testing since it exhibited the largest actuation (smallest curvature) of the measured actuators. As the stimulation frequency of the actuator has a significant influence on the forward velocity, we tested the actuator under a range of driving frequencies. We measured the swimming speed as a function of actuation frequency from 0.125 to 0.5 Hz (Figure 4), where the actuators were sequentially on or off for one-half of the cycle. We placed the actuator at one edge of the tank and allowed to come to rest prior to each experiment. We then applied the driving signal for one minute or until the actuator contacted the far wall of the tank, whichever occurred first. Following this approach, we found a peak swimming speed of ~7 mm/s at an actuation frequency of 0.25 Hz. This speed is comparable with the previously reported speed of ~8 mm/sec for a fish-like DEA actuator.[12] Lower frequencies exhibited larger bending moments during their cycles, but were at rest for a greater portion of the actuation cycle, reducing the total swimming speed. Alternatively, higher frequencies reduced the total amplitude achieved during the cycle, thereby also reducing the total swimming speed. To maximize actuation while minimizing actuator rest, we implemented manual control of the device and achieved a swimming speed of 9.2 mm/s, corresponding to 0.064 body lengths/s, as shown in Figure 5.

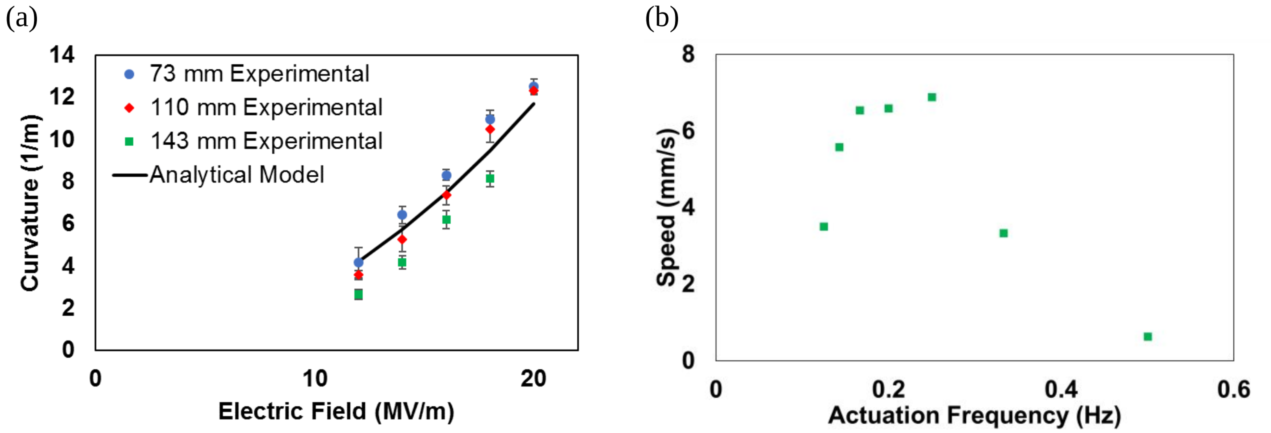

Figure 4 (a) Results from curvature measurements for three different actuators demonstrate agreement with analytical model. Error bars represent standard deviation, where n = 3 for all experiments. (b) Swimming speed as a function of actuation frequency for a 143 mm long bimorph actuator at 20 MV/m.

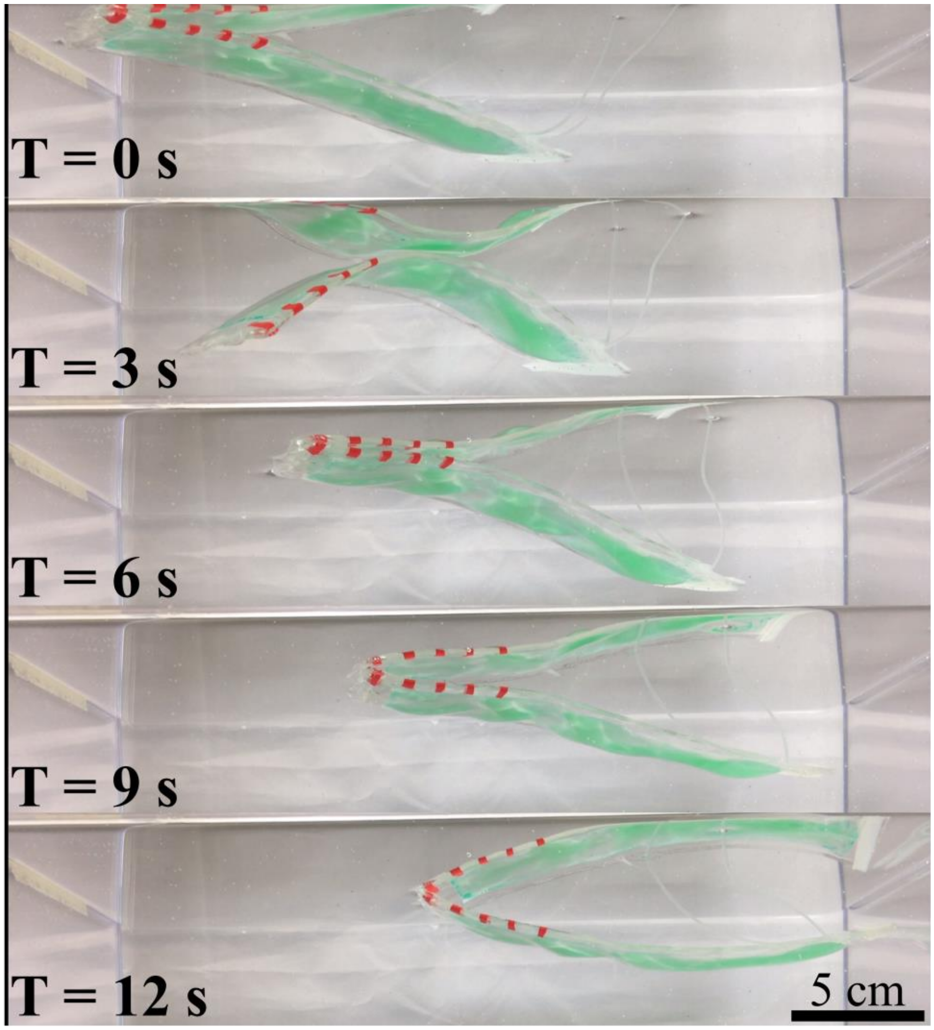

Figure 5. Images from video of bimorph actuator swimming from left to right with time indicated. Nominal electric field was 20 MV/m. Maximum speed was 9.2 mm/s.

6. CONCLUSION

In this work, we demonstrated a bimorph DEA actuator comprised of VHB dielectric layers and saltwater for compliant electrodes. Since saltwater serves as the conductive layer, we overcome buoyancy issues that may be a challenge for alternative approaches such as sealed electromechanical systems or pneumatically powered fluidic elastomer actuators. The actuator consists of a simple saline solution serving as the compliant electrodes and non-prestretched acrylic adhesive for the dielectric layers, minimizing the cost and complexity of these bimorph actuators, while also reducing the sensitivity of the electrodes to mechanical abrasion that is problematic for many other electrode materials for DEAs. By alternating the side of the tri-layer actuator to which an electrical field is applied, we achieved bi-directional motion that enables propulsion through the surrounding fluid at up to 9.2 mm/s. The tank used in this experimental setup was not significantly large with respect to the length of the actuator, therefore edge effects may not be completely neglected and will be addressed in future work. We leave optimization of the design for maximum, efficient propulsion for future work, as well as a detailed analysis of the actuation and propulsion mechanisms. This research provides an initial look into the implementation of fluid electrode actuators for submersible soft robotics and aims to open the door to low-power underwater robots towards search and rescue and environmental monitoring applications.

ACKNOWLEDGEMENTS

This work is supported by the Office of Naval Research grant number N000141712062. C. Christianson is also supported by the National Science Foundation Graduate Research Fellowship, grant number DGE-1144086.

REFERENCES

[1] Pelrine, R. E., Kornbluh, R. D., Joseph, J. P., “Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation,” Sensors Actuators A Phys. **64**(1), 77–85 (1998).

[2] Kornbluh, R. D., Pelrine, R., Joseph, J., Heydt, R., Pei, Q., Chiba, S., “High-field electrostriction of elastomeric polymer dielectrics for actuation,” Proc. SPIE **3669**(1), 149–161 (1999).

[3] Bar-Cohen, Y., Electroactive polymer (EAP) actuators as artificial muscles: reality, potential, and challenges, SPIE press (2004).

[4] Brochu, P., Pei, Q., “Advances in dielectric elastomers for actuators and artificial muscles,” Macromol. Rapid Commun. **31**(1), 10–36 (2010).

[5] Carpi, F., Bauer, S., De Rossi, D., “Stretching Dielectric Elastomer Performance,” Science (80-.). **330**(6012), 1759–1761 (2010).

[6] Anderson, I. A., Gisby, T. A., McKay, T. G., O’Brien, B. M., Calius, E. P., “Multi-functional dielectric elastomer artificial muscles for soft and smart machines,” J. Appl. Phys. **112**(4), 0–20 (2012).

[7] Pelrine, R., Kornbluh, R., Pei, Q., Joseph, J., “High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%,” Science (80-.). **287**(5454), 836–839 (2000).

[8] Carpi, F., Chiarelli, P., Mazzoldi, A., De Rossi, D., “Electromechanical characterisation of dielectric elastomer planar actuators: Comparative evaluation of different electrode materials and different counterloads,” Sensors Actuators, A Phys. **107**(1), 85–95 (2003).

[9] Keplinger, C., Sun, J.-Y., Foo, C. C., Rothemund, P., Whitesides, G. M., Suo, Z., “Stretchable, Transparent, Ionic Conductors,” Science (80-.). **341**(6149), 984–987 (2013).

[10] Tavakol, B., Holmes, D. P., “Voltage-induced buckling of dielectric films using fluid electrodes,” Appl. Phys. Lett. **108**(11), 112901 (2016).

[11] Godaba, H., Li, J., Wang, Y., Zhu, J., “A Soft Jellyfish Robot Driven by a Dielectric Elastomer Actuator,” IEEE Robot. Autom. Lett. **1**(2), 624–631 (2016).

[12] Shintake, J., Shea, H., Floreano, D., “Biomimetic Underwater Robots Based on Dielectric Elastomer Actuators,” IEEE/RSJ Int. Conf. Intell. Robot. Syst. **2**, 4957–4962 (2016).

[13] Maffli, L., Rosset, S., Ghilardi, M., Carpi, F., Shea, H., “Ultrafast all-polymer electrically tunable silicone lenses,” Adv. Funct. Mater. **25**(11), 1656–1665 (2015).

[14] Rosset, S., Shea, H. R., “Towards fast, reliable, and manufacturable DEAs: miniaturized motor and Rupert the rolling robot,” Electroact. Polym. Actuators Devices **9430**, 943009 (2015).

[15] Duduta, M., Wood, R. J., Clarke, D. R., “Multilayer Dielectric Elastomers for Fast, Programmable Actuation without Prestretch,” Adv. Mater. **28**(36), 8058–8063 (2016).

[16] Michel, S., Bormann, A., Jordi, C., Fink, E., “Feasibility studies for a bionic propulsion system of a blimp based on Dielectric Elastomers - art. no. 69270S,” Electroact. Polym. Actuators Devices **6927**, S9270–S9270 (2008).

[17] Chu, W. S., Lee, K. T., Song, S. H., Han, M. W., Lee, J. Y., Kim, H. S., Kim, M. S., Park, Y. J., Cho, K. J., et al., “Review of biomimetic underwater robots using smart actuators,” Int. J. Precis. Eng. Manuf. **13**(7), 1281–1292 (2012).

[18] Marchese, A. D., Onal, C. D., Rus, D., “Autonomous Soft Robotic Fish Capable of Escape Maneuvers Using Fluidic Elastomer Actuators,” Soft Robot. **1**(1), 75–87 (2014).

[19] Valdivia y Alvarado, P., Youcef-Toumi, K., "Design of Machines With Compliant Bodies for Biomimetic Locomotion in Liquid Environments," J. Dyn. Syst. Meas. Control **128**(1), 3 (2006).

[20] Fish, F. E. E., Lauder, G. V. V., "Passive and Active Flow Control By Swimming Fishes and Mammals," Annu. Rev. Fluid Mech. **38**(1), 193–224 (2006).

[21] Raj, A., Thakur, A., "Fish-inspired robots: design, sensing, actuation, and autonomy—a review of research," Bioinspir. Biomim. **11**(3), 31001, IOP Publishing (2016).